Introduction to Boundary Layer Meteorology

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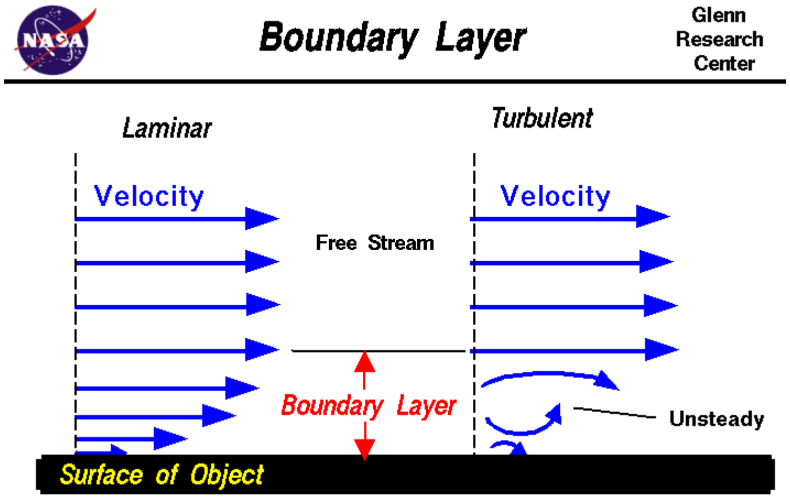
Boundary Layer Definitions

- The layer of fluid in the immediate vicinity of a boundary where the effects of viscosity are significant
  - Viscosity causes fluid to “stick” to wall (no-slip)
  - E.g., on a wing bl thickness ~ 1 cm
  - May be laminar or turbulent



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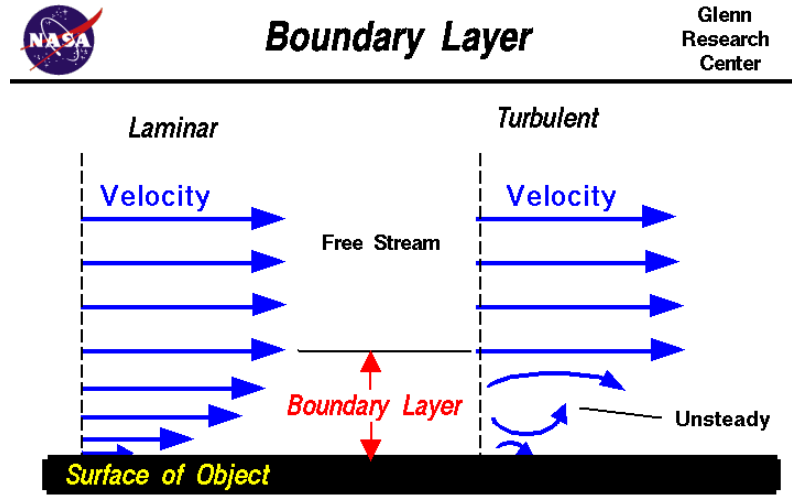
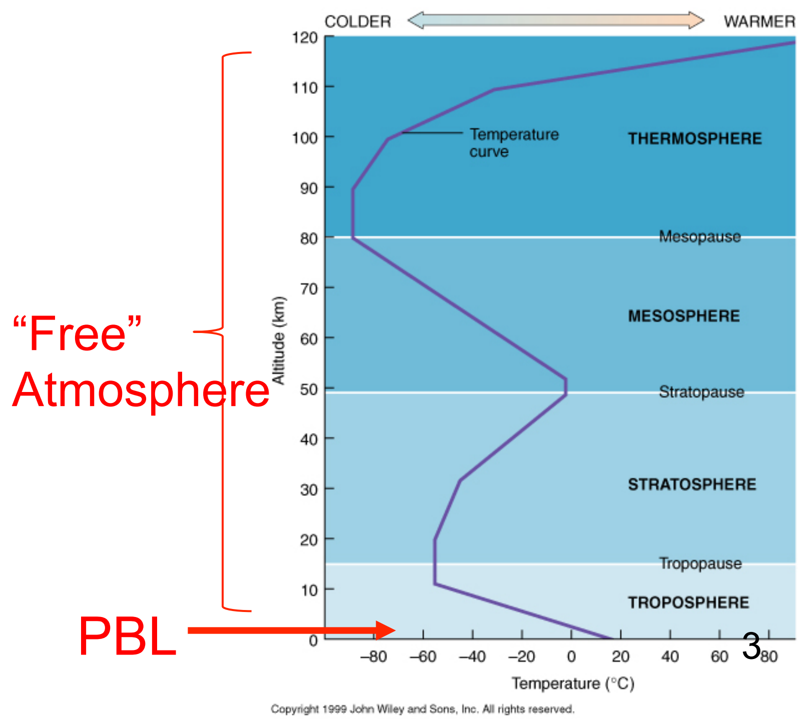
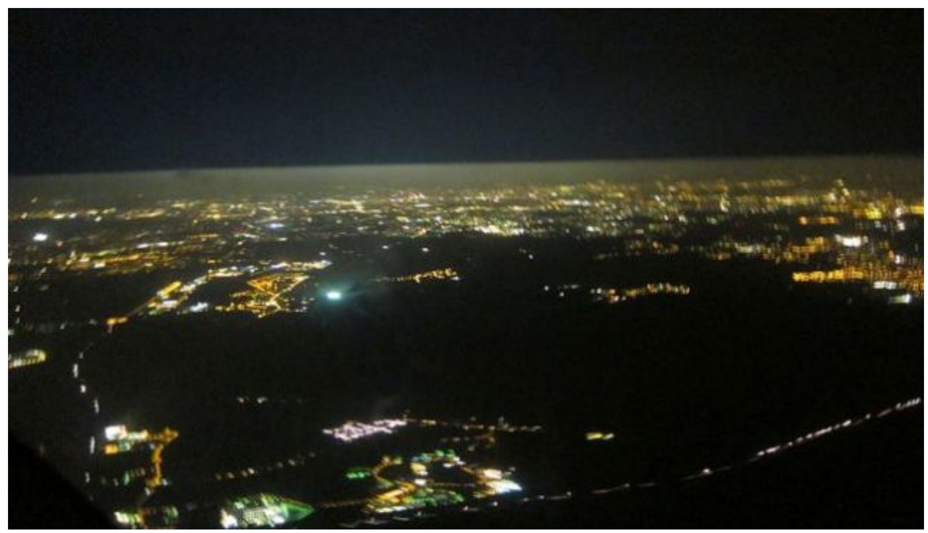
- Near the Earth’s surface:
  - Affected by surface temperature, moisture etc.
  - Atmospheric Boundary Layer (ABL)
  - Planetary Boundary Layer (PBL)
  - Always turbulent
  - Lowest part of troposphere (typically 100m-3km)
  - Where most UAVs fly





Effects of PBL

- Enhances vertical shear
- Allows horizontal shear around obstacles
- Allows wind convergence towards regions of low pressure
  - Change in wind direction with height
  - Forces upward motion and clouds
- Mixes heat, momentum, moisture from surface and from aloft
- Creates low-level inversion at top
- Contains fog and pollution



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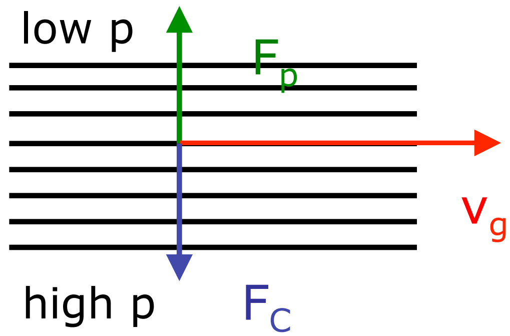
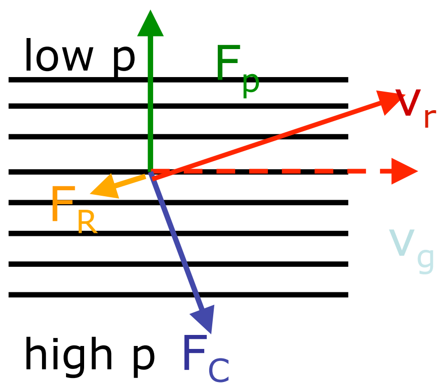
Wind Profile in the PBL

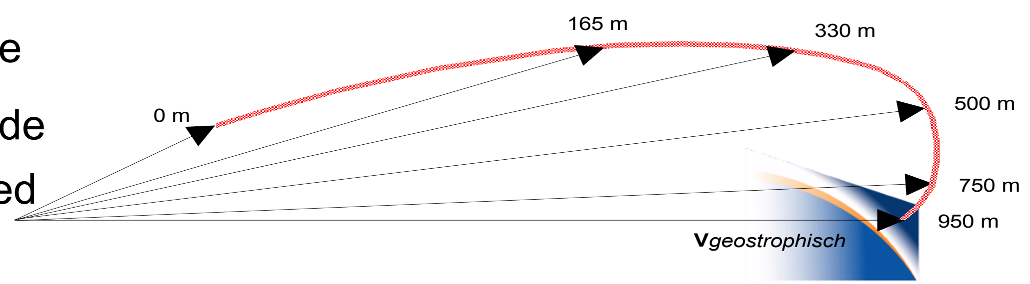
- In the free atmosphere (free of friction), the wind is geostrophic (i.e., parallel to isobars due to the balance between pressure gradient and Coriolis force)



- Close to the surface, friction will cause a deviation of the wind direction from geostrophic (flow from high to low pressure)



- Consequently:
  - wind speed increases with altitude
  - wind direction changes with altitude in the form of a spiral, the so-called **Ekman Spiral**



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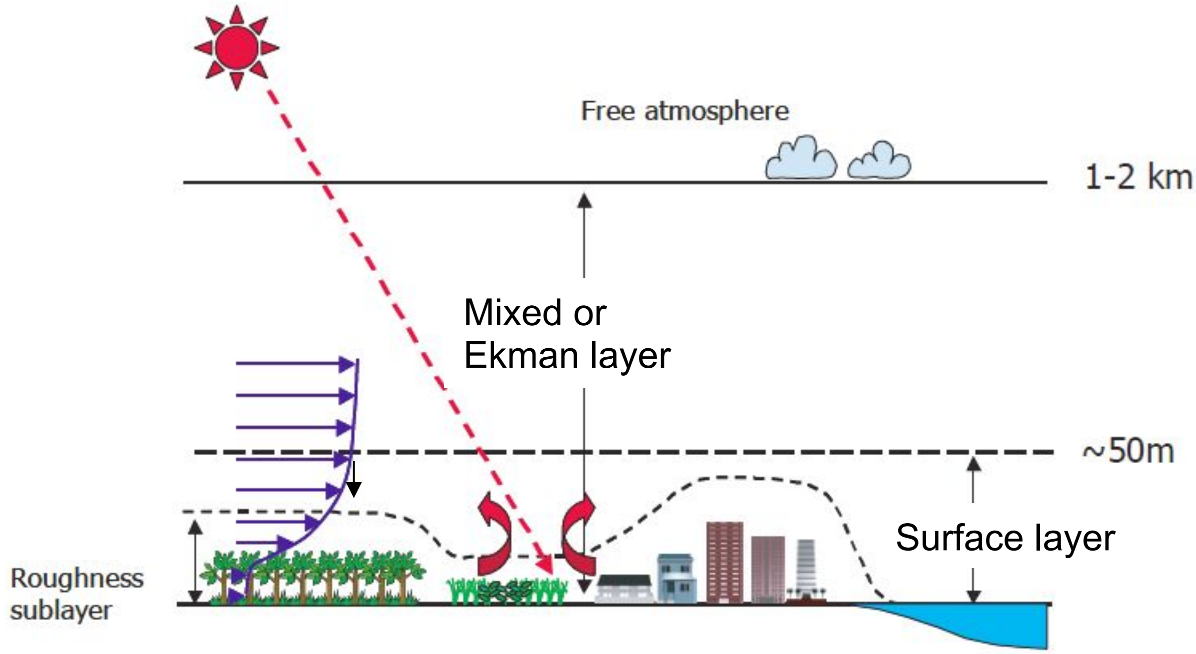
Structure of PBL



- Roughness Layer: Flow highly irregular; strongly affected by the nature of the individual roughness features (grass, trees, buildings).
- Surface Layer: About 1/10 of PBL. Strong vertical wind shear. Intense small scale turbulence generated by surface roughness and convection.
- Mixed or Ekman Layer: Turbulence effects smaller, wind speed nearly constant with height, but change in wind direction with height. Usually topped by a temperature inversion

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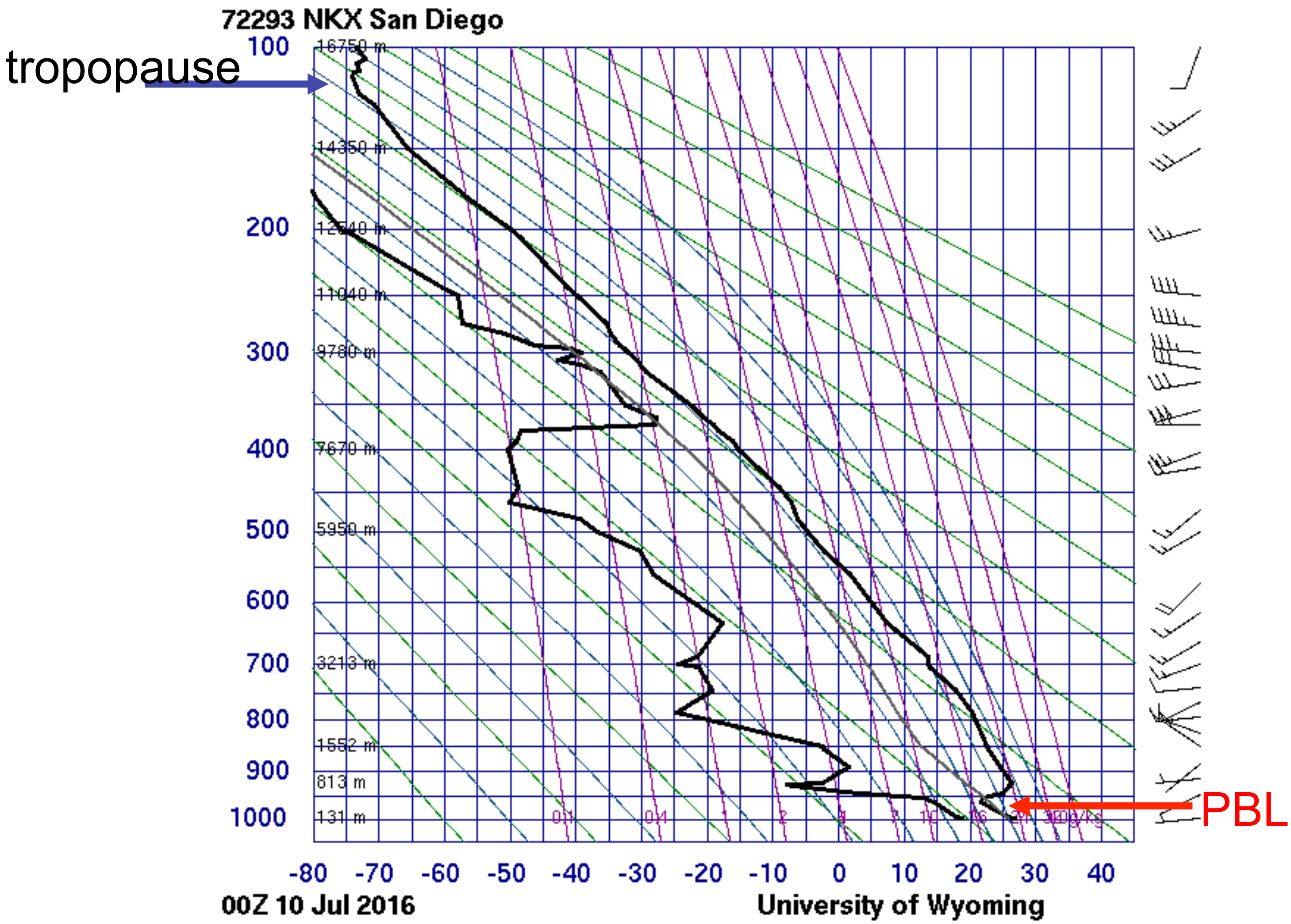
Example sounding showing PBL and tropopause (San Diego 4 PM LT)



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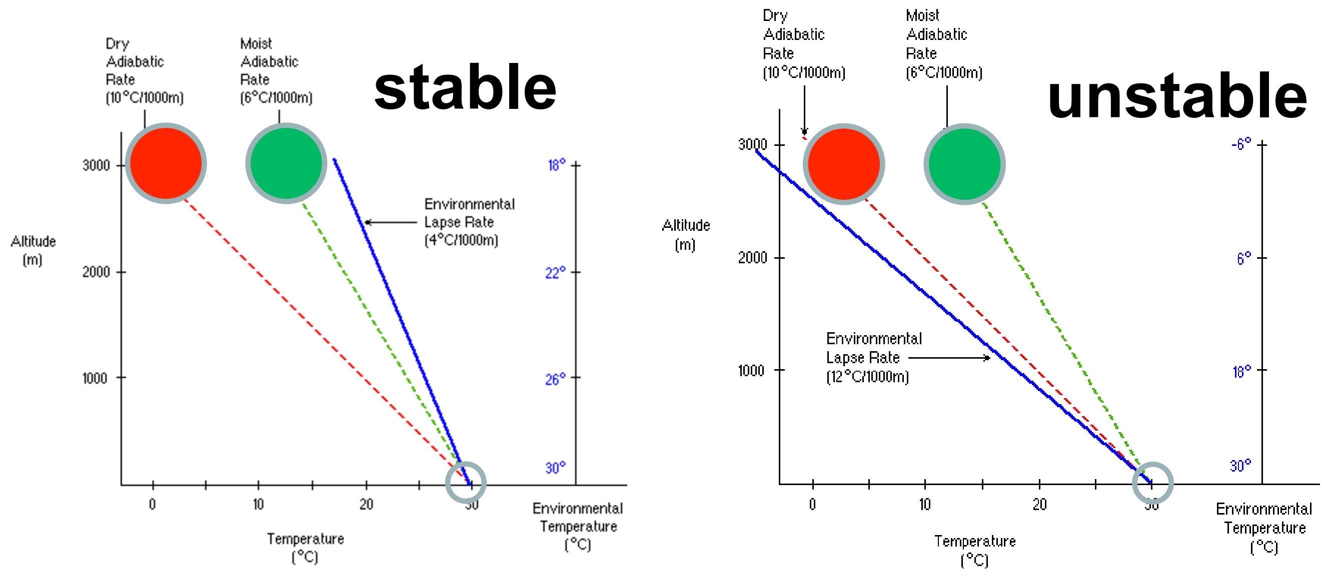
PBL character depends on stability of air within it



Lifted “parcel” of air cools at a standard rate as it rises toward lower pressure

•Stable if parcel is cooler than environment -> turbulence suppression

•Unstable if parcel is warmer than environment -> turbulence production

Lifted “parcel” of air maintains potential temperature (θ) as it rises toward lower pressure

$\Delta\theta/\Delta z)$atmosphere > 0 stable

$\Delta\theta/\Delta z)$atmosphere < 0 unstable

$\Delta\theta/\Delta z)$atmosphere = 0 neutral (well mixed)

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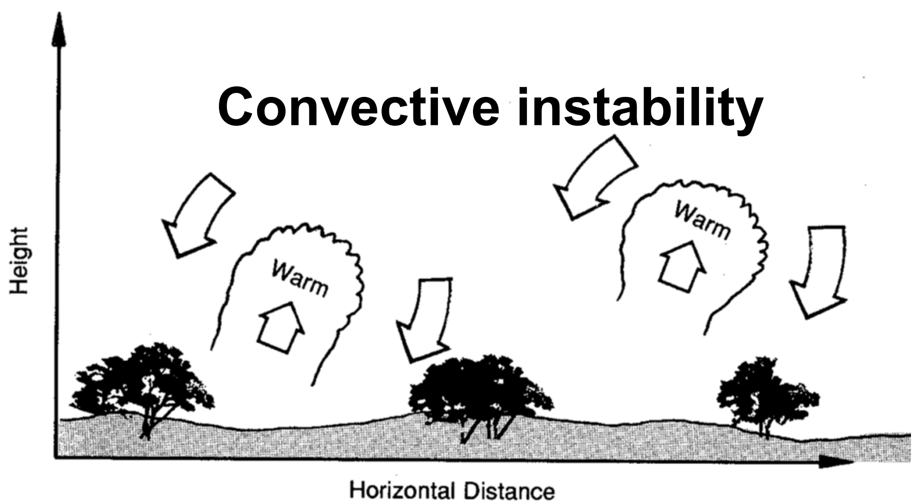
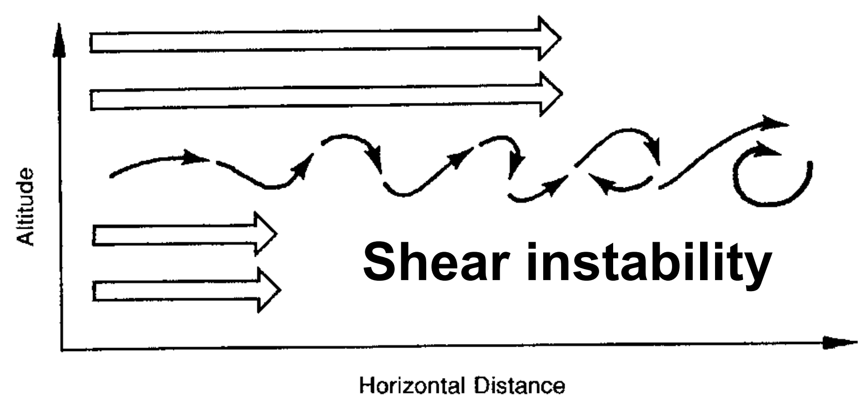
PBL types in terms of stability

- Convective Boundary Layer (CBL)
  - Thermally driven by surface heating
  - Develops during the day
  - Convectively unstable leading to moderate to strong turbulence and vertical mixing

- Stable Boundary Layer (SBL)
  - Driven by surface cooling
  - Develops at night
  - Mainly stable but local regions of shear instability and turbulence





Source: P. Lester, "Turbulence – A new perspective for pilots," Jeppesen, 1994

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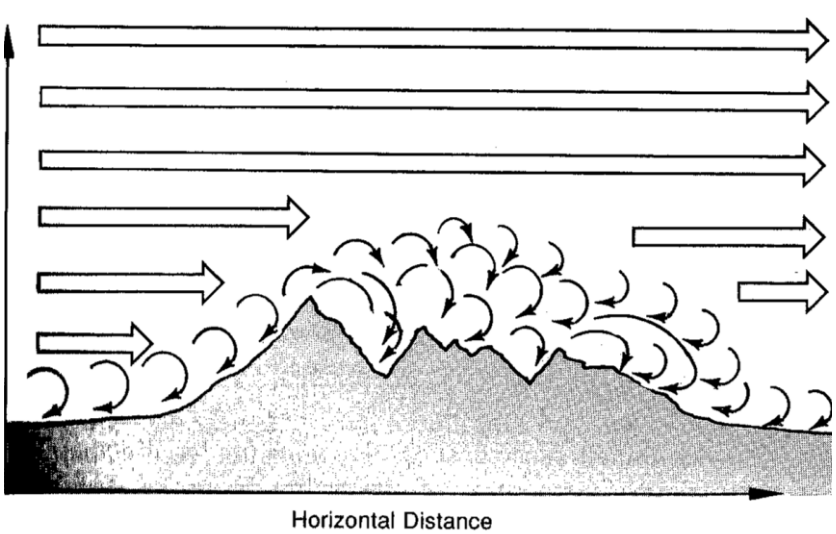
Other sources of turbulence in the PBL

- Terrain-induced turbulence
  - Both shear-induced and convective
  - Produces complicated 3d structure



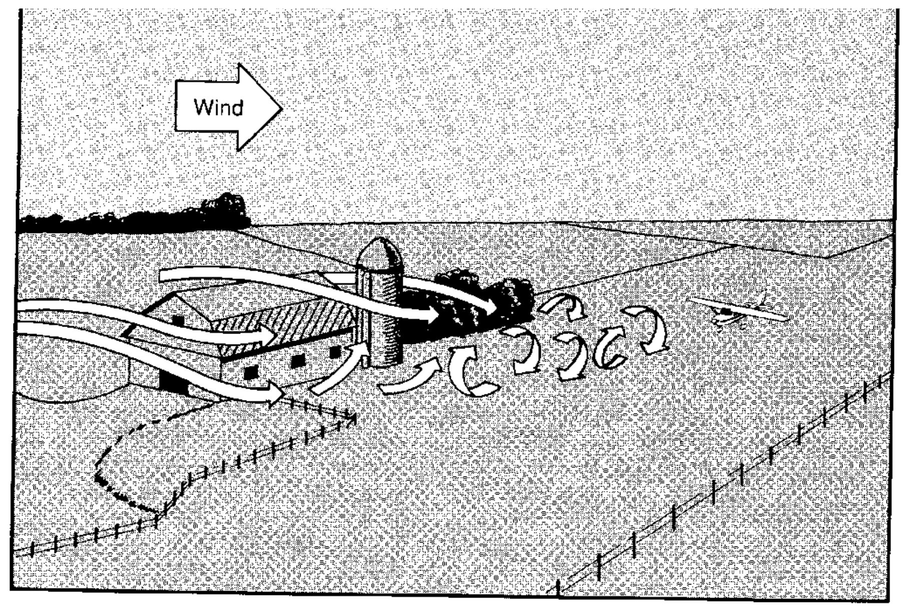


Figure 2-2. Both natural and man-made obstacles produce turbulent eddies downwind.

Source: P. Lester, "Turbulence – A new perspective for pilots," Jeppesen, 1994

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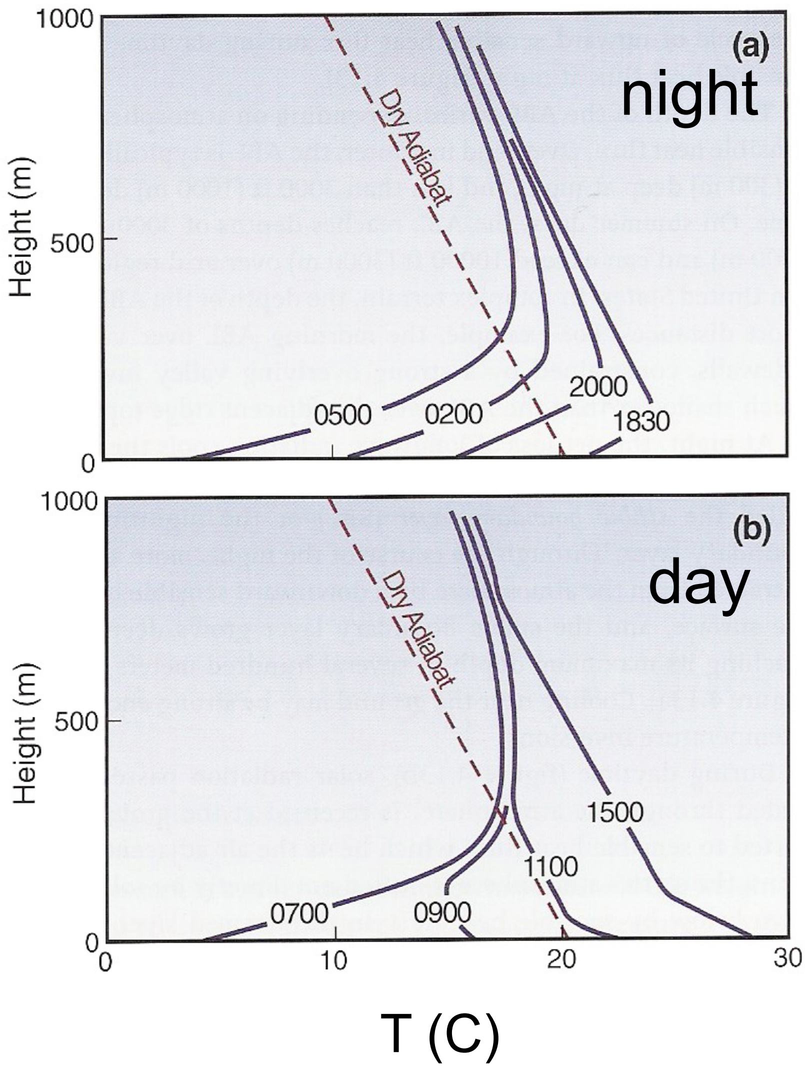
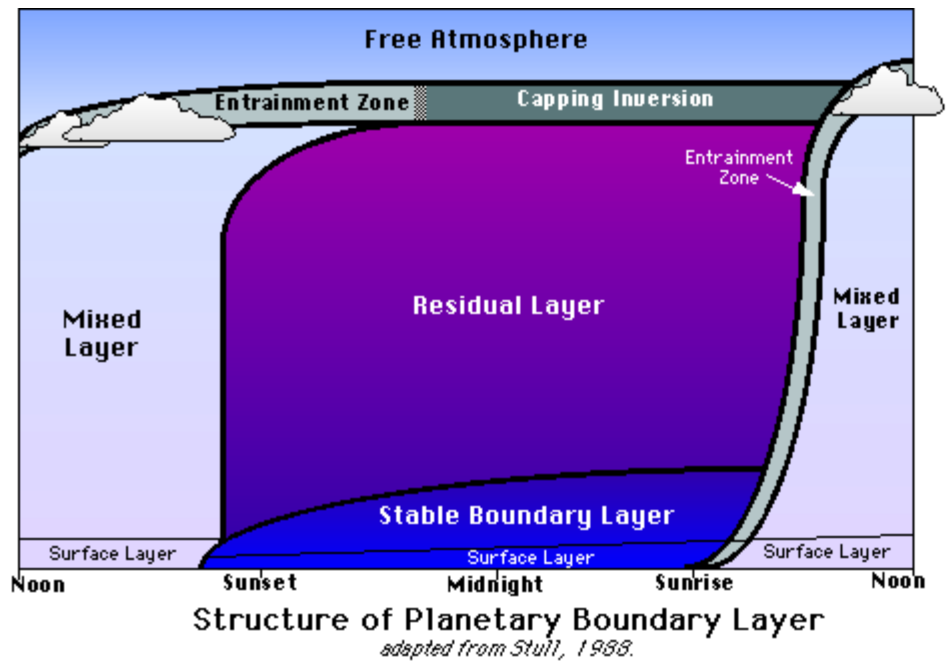
Diurnal cycle of PBL



From Whiteman, Mountain Meteorology



Boundary layer is much thinner at night:
Day ~ 1 km, Night ~ few hundred meters

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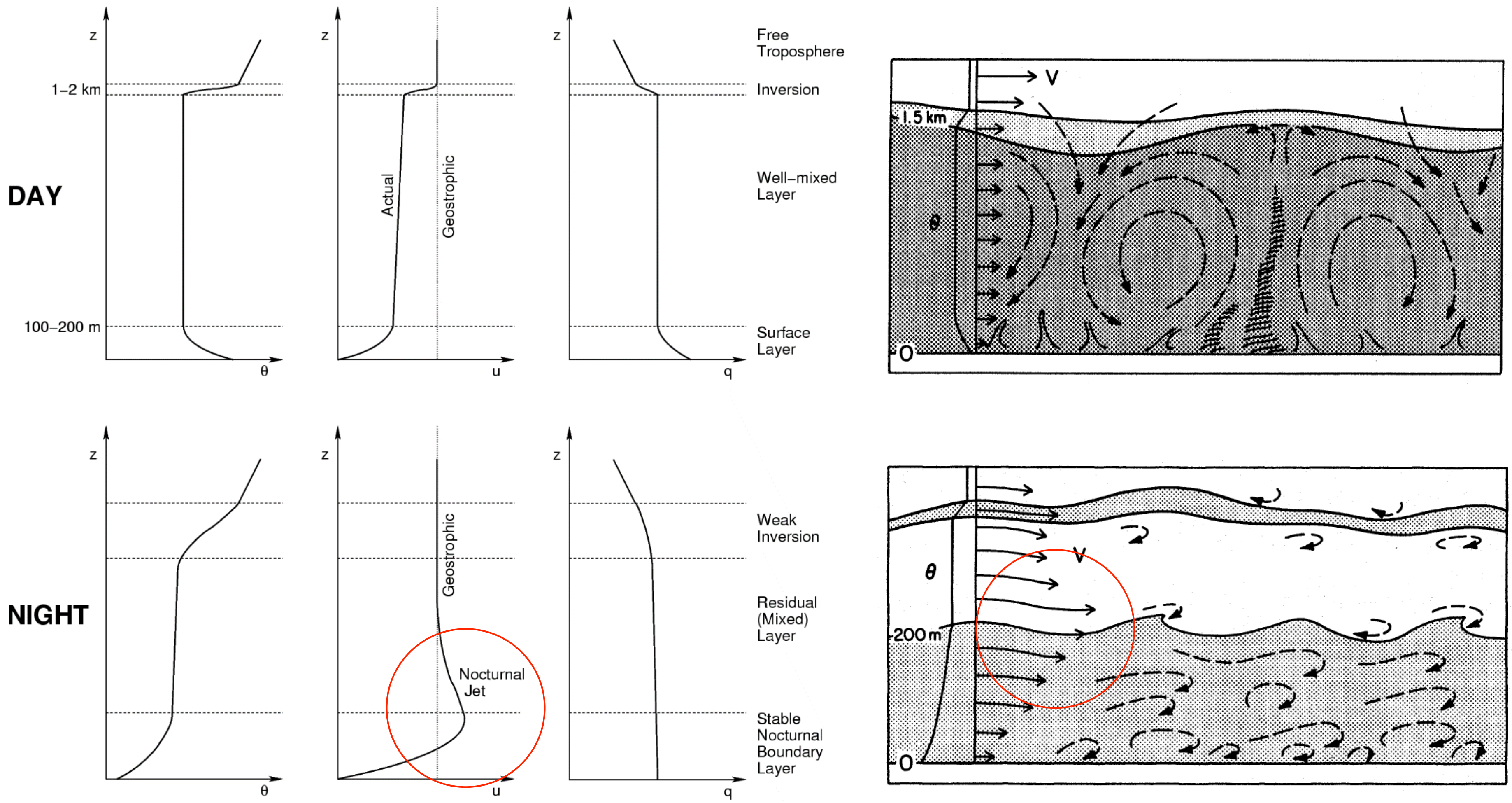
Structure of PBL (cont.)



(Left) Typical PBL profiles of potential temperature, wind and humidity over land in midlatitudes during cloudless conditions.
(Right) Schematics of the typical PBL circulation and eddy structure of the ABL in the day and night (from Kaimal and Finnigan 1994).

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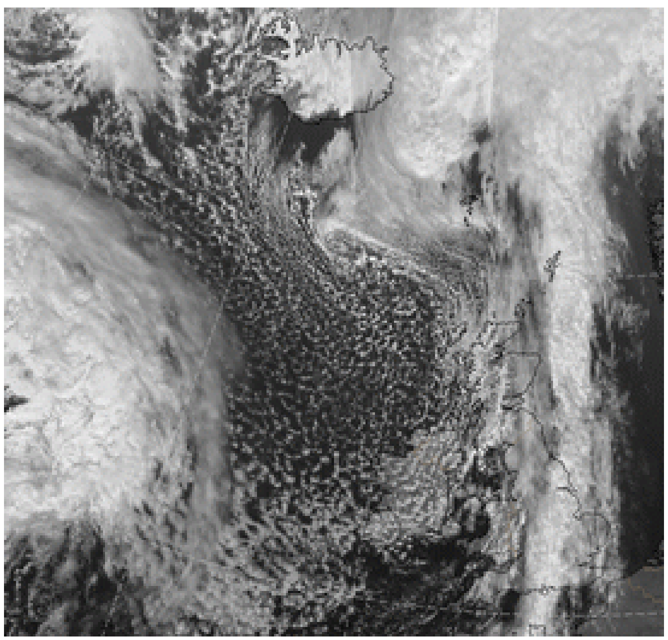
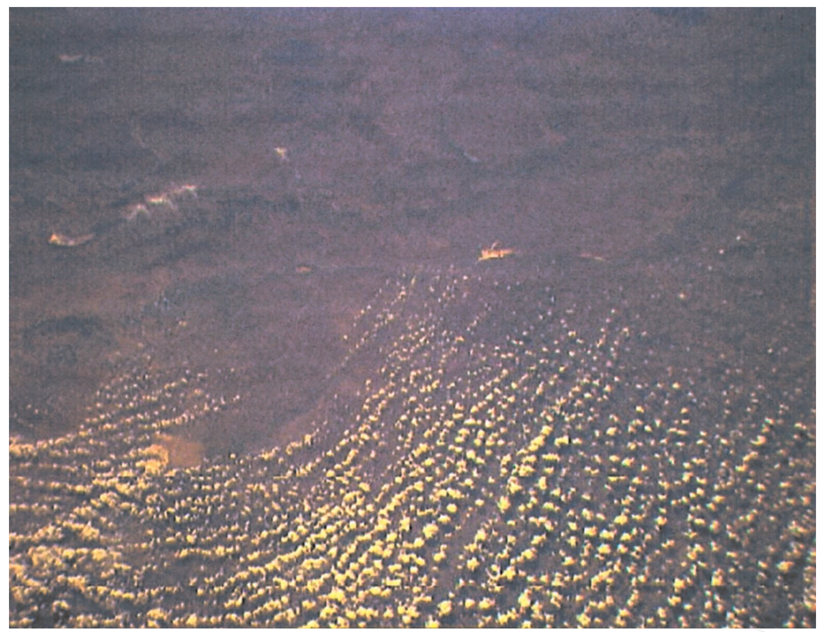
PBL Organization

- Sometimes organized as cells or rolls
  - Cells (honeycomb structure) in small shear
  - Rolls favored in larger shears with shear vector aligned along roll axis
  - Both can be visible in cloud images



Cells: 23 September 2005/12.00 UTC - Meteosat-8 HRVIS



Cloud streets over Oklahoma, taken by the *Endeavor* crew during NASA Mission STS068. Date unknown. (Courtesy of the Johnson Space Center JSC Digital Image Collection.)

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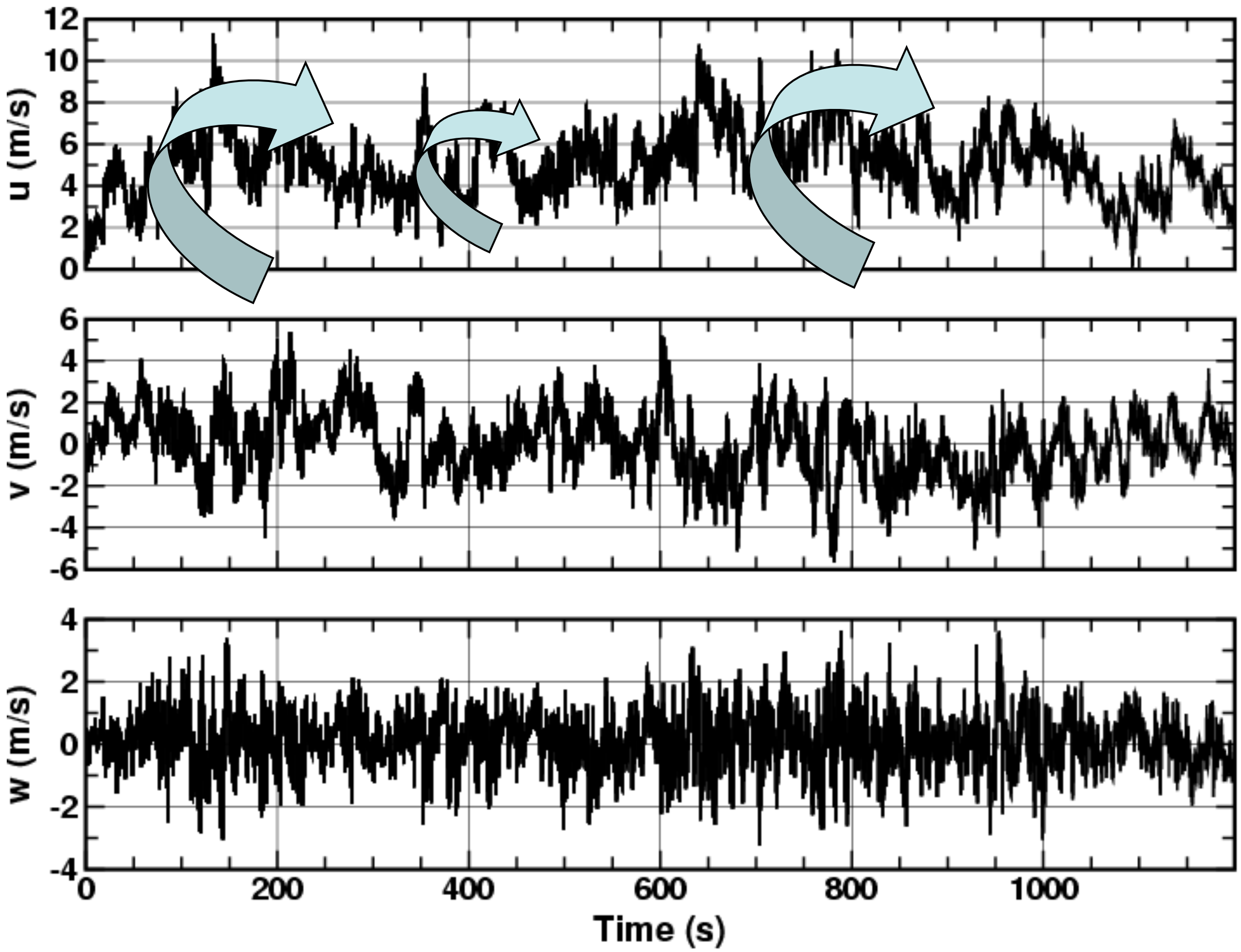
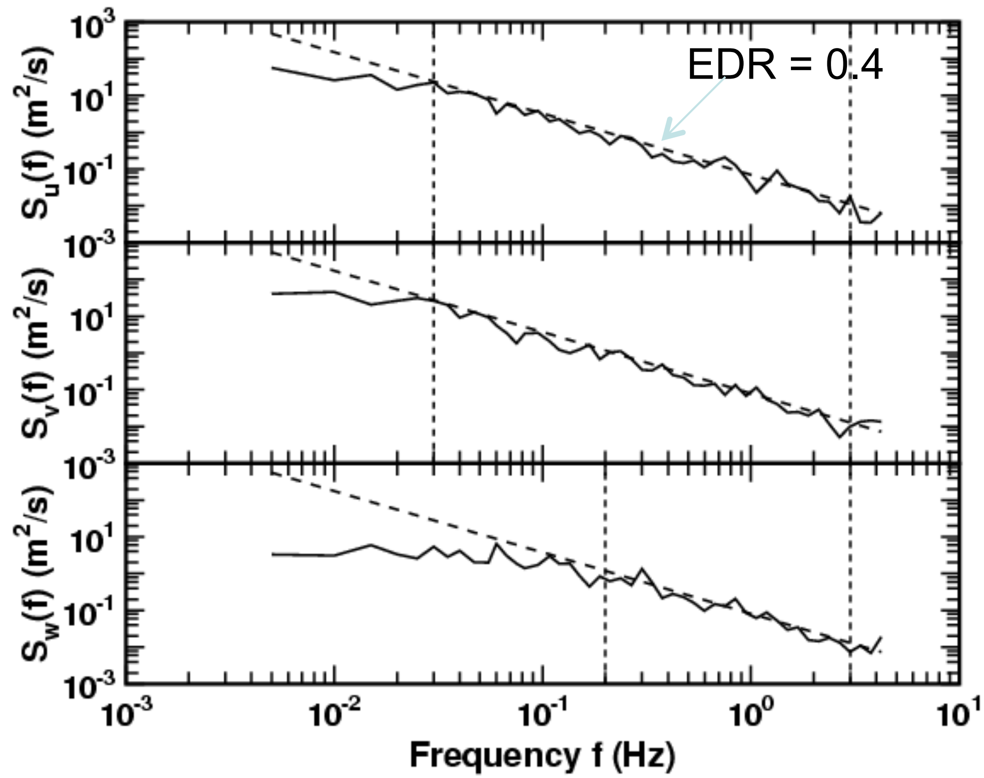
Turbulence character – daytime boundary layer



Sonic anemometer data example: mean ~ 5 m/s, σ ~ 1.5 m/s, gust ~ 11 m/s

Description of turbulence

- Intensity of fluctuations
- Eddy size or length scale
- But aircraft respond to a range of eddy sizes so need to describe turbulence in terms of a spectrum of sizes
  - Relate the level of the spectrum to turbulence intensity
  - Downscale cascade from large to small scales, usually power law $f^{-5/3}$
  - Rate of energy transfer is given by the "energy dissipation rate" (ε) units m^2/s^3
  - Level of spectrum ~ ε
  - RMS of vertical accelerations experienced by an aircraft ~ $\varepsilon^{1/3}$ (=EDR units $m^{2/3}/s$). For heavy ac
    - Moderate ~ 0.3
    - Severe ~ 0.5



Eddy frequency spectrum from anemometer trace on previous slide: levels are about the same in all directions=isotropic

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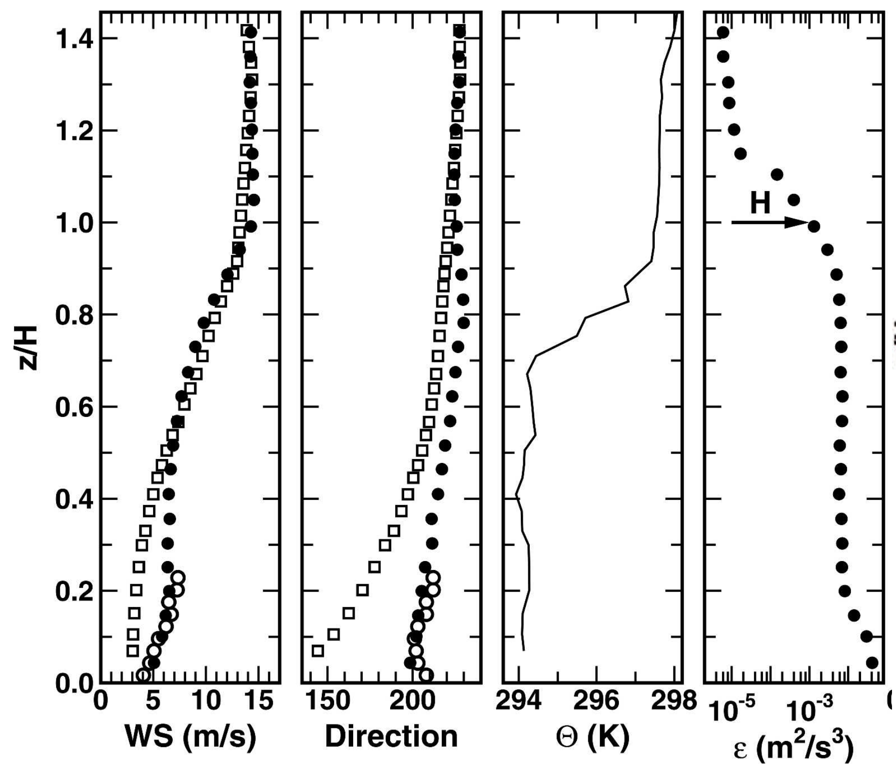
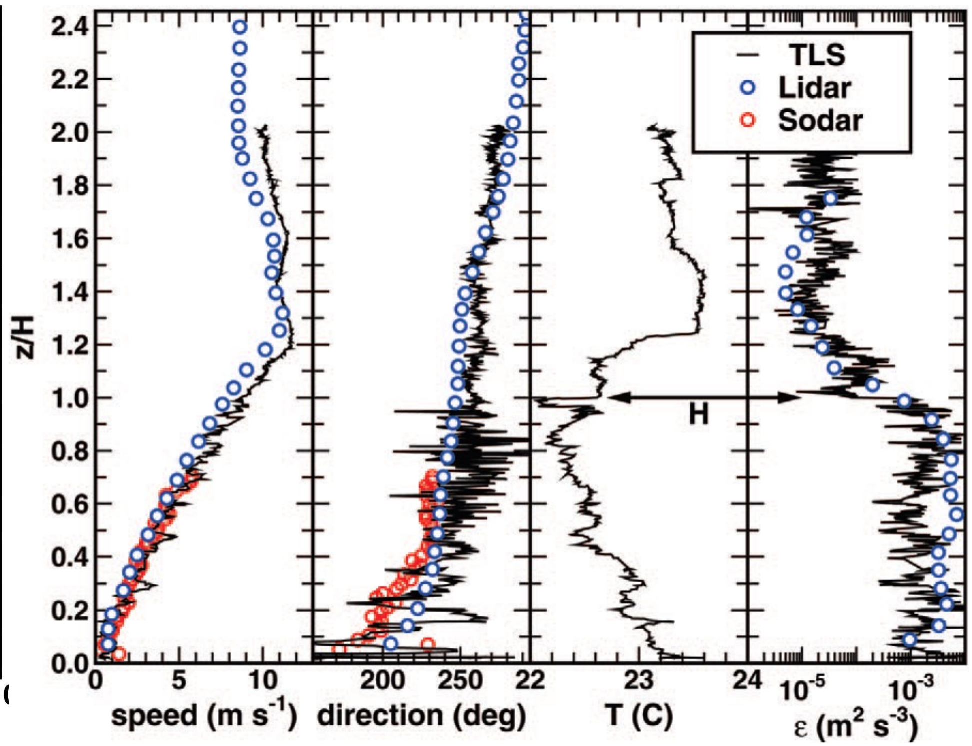
Measured PBL profiles





Daytime urban BL
(rawinsonde,lidar,sodar)
Frehlich et al. JAMC 2006

Nighttime urban BL
(kite,lidar,sodar)
Warner et al. BAMS 2007

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Simulations of PBL

- Observations do not allow 3D+time examinations of PBL evolution
- Theory is too simplified to be useful
- Great success over last decade using computer simulations
  - Direct Numerical simulation (DNS): Very fine scale, so resolves most eddies
    - Solves full governing equations including molecular viscosity
    - Grid spacing ~ cm
    - Extremely computationally expensive, still not all scales are covered
  - Large eddy simulation (LES): Only largest eddies are resolved; smaller less energetic eddies are parameterized
    - Very successful with CBL, not so much with SBL
    - Grid spacing typically 10s of m
    - Computationally intensive for large areas

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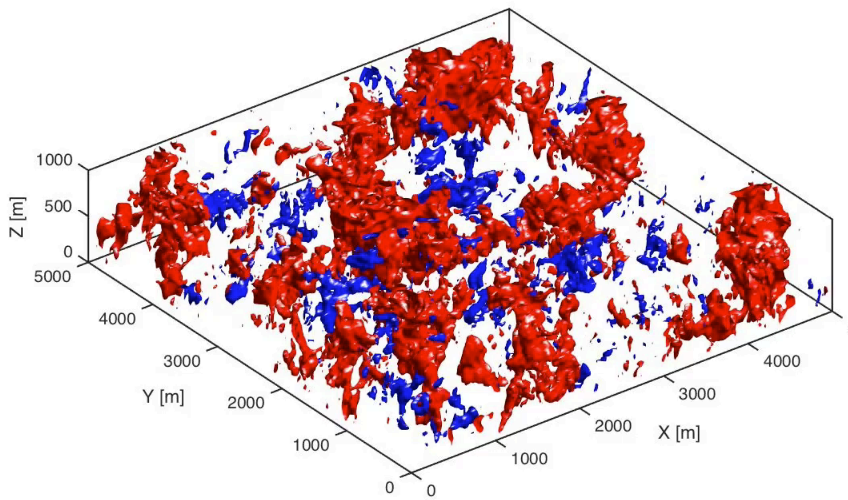
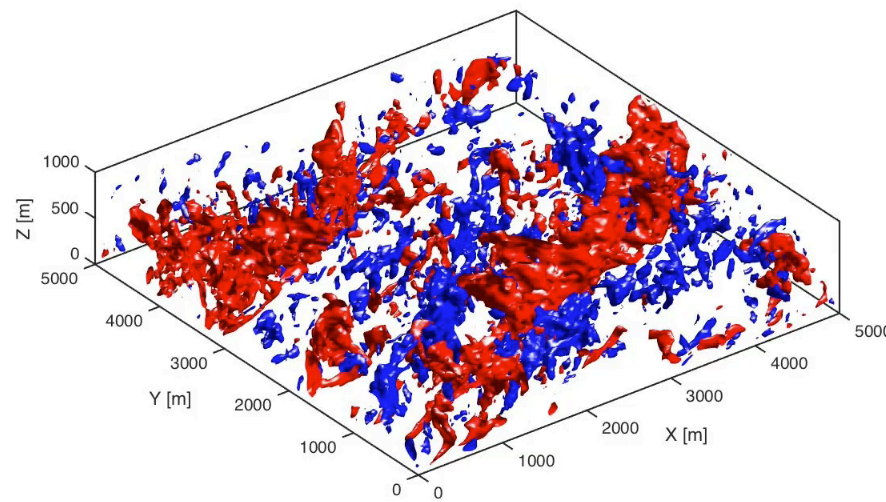
LES of cells/rolls (dx=20m)





Convective cells (red: +w, blue: -w)
U_g=5 ms^{-1}, H_s=235 Wm^{-2}

Convective rolls (red: +w, blue: -w)
U_g=20 ms^{-1}, H_s=83 Wm^{-2}

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PBL/ABL meteorology - Key points

- Lowest layer of the atmosphere where most UAVs fly
- Transition layer from no-slip at surface to free atmosphere wind aloft
  - Wind increases and turns with height
  - Typically 100m- 3km depth
  - Intricately linked to turbulence
  - Depends on surface roughness (e.g. urban vs. rural)
  - Different character daytime vs nighttime
    - Daytime deep, convectively unstable, turbulence everywhere, well-mixed
    - Nighttime shallow, stable but contains very thin turbulent layers

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